

Interferometric Observations of Powerful CO Emission from three Submillimeter Galaxies at $z = 2.39, 2.51$ and 3.35 ¹

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ABSTRACT

We report IRAM millimeter interferometry of three $z \sim 2.4$ to 3.4 , SCUBA deep field galaxies. Our CO line observations confirm the rest-frame UV/optical redshifts, thus more than doubling the number of confirmed, published redshifts of the faint submm-population and proving their high- z nature. In all three sources our measurements of the intrinsic gas and dynamical mass are large (10^{10} to $10^{11} M_{\odot}$). In at least two cases the data show that the submm sources are part of an interacting system. Together with recent information gathered in the X-ray, optical and radio bands our observations support the interpretation that the submm-population, at least the radio detected ones, consists of gas rich (gas to dynamical mass ratio ~ 0.5) and massive, interacting starburst/AGN systems.

Subject headings: cosmology: observations - galaxies: formation - galaxies: high-redshift - galaxies: evolution

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1. Introduction

The extragalactic far-IR/submm background is probably dominated by luminous infrared galaxies (LIRGs/ULIRGs: $L_{\text{IR}} \sim 10^{11.5}$ to $10^{13} L_{\odot}$) at $z \gtrsim 1$ (e.g. Smail et al. 1997; Bertoldi et al. 2002; Scott et al. 2002; Cowie et al. 2002). However, far-IR/submm sources in most cases have relatively poorly known positions and frequently have only weak counterparts in the rest-frame UV and optical (Smail et al. 2000, 2002; Dannerbauer et al. 2002). As a result redshifts have thus far been confirmed with CO interferometry for only two of the ~ 100 detected systems (Blain et al. 2002). Recently a subgroup of the authors have obtained optical spectroscopic redshifts for a number of sources detected with the SCUBA camera at $850\mu\text{m}$, to a large extent aided by more precise positions derived from deep 1.4 GHz VLA observations of the same fields. Here we report the first results on the millimeter CO line follow-up of these submm sources. We believe these observations mark a sensitive breakthrough in the notoriously difficult study of the faint far-IR/submm galaxy population.

2. Observations

The observations were carried out between late summer 2002 and winter 2003 with the IRAM Plateau de Bure interferometer, consisting of six 15m-diameter telescopes. We used the compact D configuration, and for follow-up observations of two of the sources the more extended BC configurations. The correlator was configured for CO line and continuum observations to simultaneously cover 580 MHz in the 3 mm and 1.3 mm bands. The frequency settings were adjusted for all three sources to optimize the CO line centering in the bandpass. SMMJ04431+0210 was observed between Sep '02 and Feb '03 in D and BC configurations for a total integration time of 22 hrs. SMMJ09431+4700 was observed in D configuration only, in Nov '02, for 13 hrs. SMMJ16368+4057 was observed between Sep '02 and Feb '03 for 24 hrs. All sources were observed in very good observing conditions. We calibrated the data using the CLIC program in the IRAM GILDAS package. Passband calibration used one or more bright quasars. Phase and amplitude variations within each track were calibrated out by interleaving reference observations of nearby quasars every 20 minutes. The overall flux scale for each epoch was set on MWC 349. After flagging bad and high phase noise data (less than 2% at 3 mm), we created data cubes in natural weighting.

3. Results

Figures 1 and 2 show the CO spectra and maps. The derived properties are listed in Tables 1 and 2. We adopt a flat, $\Omega_M = 0.3$ Λ -cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. To convert CO luminosities to gas masses, including a 37% correction for helium, we adopt, under the assumption of constant brightness temperature for the lowest rotational transitions from 1-0 to 4-3, a factor $\alpha = 0.8 \text{ M}_\odot / (\text{K km s}^{-1} \text{ pc}^2) = 0.2\alpha$ (Galactic), as derived from observations of $z \sim 0.1$ ULIRGs (Downes & Solomon 1998). The gas masses are probably uncertain by a factor of at least 2. We estimate dynamical masses from $M_{\text{dyn}} \sin^2 i \text{ (M}_\odot) = 4 \times 10^4 \Delta v_{\text{FWHM}}^2 R$. Here we assume that the gas emission comes from a rotating disk of outer radius R (kpc) observed at inclination angle i . In a merger model the dynamical masses would be a factor of 2 larger (Genzel et al. 2003). The numerical constant incorporates a factor of 2.4 between observed FWHM velocity width of the line emission, Δv_{FWHM} (km/s), and the product of rotation velocity and $\sin i$. This factor is estimated from model disks taking into account local line broadening, beam and spectral smearing. We deduce IR luminosities from the $850 \mu\text{m}$ continuum flux densities S by adopting a modified greybody model ($T = 40 \text{ K}$) with $\propto \nu^{1.5}$ dependent emissivity, such that in the range from $z = 2$ to 3.5 $L_{\text{IR}} \text{ (L}_\odot) = 1.9 \times 10^{12} S_{850}$ with S_{850} in mJy (Blain et al. 2002). These luminosities are uncertain by a factor of 2 to 3 since dust temperature and emissivity law may vary from source to source (Blain et al. 2003). In the following, all linear sizes, masses and luminosities are corrected for the foreground lensing factors in Table 2.

SMMJ04431+0210 ($z = 2.51$) was originally found in the SCUBA Lens Survey ($S_{850} = 7.2 \text{ mJy}$; Smail et al. 1997; 2002). It is located behind the $z = 0.18$ cluster MS0440+02. Smail et al. (1999) identified the submm source with the $K = 19.4$ extremely red object (ERO) N4 about $3''$ NW of an edge-on cluster spiral galaxy N1 (N4: $R - K = 6.3$; Frayer et al. 2003). Frayer et al. deduced a redshift of $z = 2.5092 \pm 0.0008$ from $\text{H}\alpha / [\text{N II}] / [\text{O III}]$ line emission. The rest frame optical line ratios suggest that N4 is a composite starburst/narrow line AGN. We adopt the foreground lens magnification of 4.4 deduced by Smail et al. (1999). Our BCD configuration data show a strong CO 3-2 line centered at $z = 2.5094 \pm 0.0002$, $+17 (\pm 17) \text{ km s}^{-1}$ redward of the nominal redshift of the $\text{H}\alpha$ line. The line width is FWHM $350 \pm 60 \text{ km s}^{-1}$, somewhat smaller than that of $\text{H}\alpha$ (520 km s^{-1}). The integrated CO line flux corresponds to a total gas mass of $8 \times 10^9 \text{ M}_\odot$. Most of the CO line emission comes from within $1''$. The CO emission centroid is $1.1''$ SW of the near-IR position of N4, as determined by a new astrometric solution of the near-IR/radio astrometry we obtained by comparing USNO stars with radio sources in the field (N4: $04^{\text{h}}43^{\text{m}}07.25^{\text{s}} 02^\circ10'24.4''$ (J2000); the uncertainty is $\pm 0.5''$). This new position of N4 is $2.2''$ E and $0.6''$ S of the position reported by Smail et al. (1999) based on the APM coordinate system. The 1.3 mm continuum data show a marginally significant detection (1.1 mJy , 3.7σ) near the position of N4. We set a limit to

the CO 7-6 emission of $\leq 0.8 \text{ Jy km s}^{-1}$ (2σ). For comparison, the $\text{H}\alpha$ emission exhibits a velocity gradient of $\geq 400 \text{ km s}^{-1}$ over about $1''$ and along the slit at p.a. -14° , that is, at about 50° relative to the direction of the extended CO emission. The centroid of the $\text{H}\alpha$ emission is on N4. It thus appears that the rest-frame submm and optical observations sample a similar region (size $\sim 1''$) but with some differences in the spatial structure in the two wavelength ranges. SMMJ04431+0210 has by far the lowest intrinsic IR luminosity ($3 \times 10^{12} L_\odot$) and gas/dynamic mass of our three galaxies. We deduce an upper limit to the dynamical mass of $4.5 \times 10^9 \sin^{-2} i M_\odot$ for a source diameter of $\leq 1''$. In terms of luminosity, gas and dynamical mass, SMMJ04431+0210 thus resembles local ULIRGs.

SMMJ09431+4700 ($z=3.35$) was first identified by Cowie et al. (2002) in a deep SCUBA map of the $z=0.41$ cluster Abell 851 ($S_{850}=10.5 \text{ mJy}$). They estimated a foreground lens magnification of 1.2. Ledlow et al. (2002) proposed that the counterpart of the SCUBA source is the 1.4 GHz radio source H6 ($72 \mu\text{Jy}$), for which they identified a redshift of $z=3.349$ from $\text{Ly}\alpha$. H6 appears to be a UV bright, narrow line Seyfert 1 galaxy. We find strong CO 4-3 emission with a flat-topped profile and FWHM 420 km s^{-1} centered at $z=3.3460 \pm 0.0001$, $-207 (\pm 7) \text{ km s}^{-1}$ blueward of the nominal $\text{Ly}\alpha$ redshift. The 1.3 mm continuum was also detected with $2.3 \pm 0.4 \text{ mJy}$ and is centered at the same position. CO line and continuum emission are centered $3.8''$ W and $1''$ S of the position of H6 (24 kpc in the source plane), positionally coincident with the second, weaker 1.4 GHz source H7 ($55 \mu\text{Jy}$) at $09^{\text{h}}43^{\text{m}}03.7^{\text{s}} 47^{\circ}00'15.1''$ (J2000) (Fig.2). H6 and H7 are very probably physically related. The gas mass deduced from the CO 4-3 flux is $2.1 \times 10^{10} M_\odot$, and the IR luminosity based on S_{850} is $1.7 \times 10^{13} L_\odot$. For an assumed source size of $1''$ of H7 we infer a dynamical mass of $2.5 \times 10^{10} \sin^{-2}(i) M_\odot$. A lower limit to the virial mass of the H6/7 system is $6 \times 10^{10} M_\odot$.

SMMJ16368+4057 ($z=2.39$, Elais N2 850.4) was identified by Ivison et al. (2002; $S_{850}=8.2 \text{ mJy}$) in the 8mJy SCUBA blank field survey of the Elais N2 field (Scott et al. 2002) with a $220 \mu\text{Jy}$ bright 1.4 GHz radio source. Optical spectroscopy by Chapman et al. (2003) and Smail et al. (2003) showed bright $\text{Ly}\alpha$, N V, C IV, [O II] and [O III] emission with a complex spatial and velocity structure. Smail et al. (2003) proposed that N2 850.4 consists of a UV bright starburst galaxy at $z=2.380 (\pm 0.002)$, plus a Seyfert 2 galaxy at $z=2.384 (\pm 0.003)$. There is no evidence for gravitational lensing. We also detected the 1.3 mm continuum emission ($2.5 \pm 0.4 \text{ mJy}$) and CO 7-6 emission. The CO 3-2 emission is very broad (840 km s^{-1} FWHM) and is centered at $z=2.3853 (\pm 0.0004)$, $+115 \text{ km s}^{-1} (\pm 36 \text{ km s}^{-1})$ redward of the nominal redshift of the Sey2 nucleus. CO 7-6 emission is tentatively detected in a narrow component centered -200 km s^{-1} of the CO 3-2 line centroid. At the 7-6 peak the observed 7-6/3-2 brightness temperature ratio is 0.5 ± 0.2 . Large velocity gradient modeling of this ratio indicates that the higher excitation CO 7-6 emission may come from a specific warm ($T \geq 50 \text{ K}$) and dense ($n(\text{H}_2) \geq 10^4 \text{ cm}^{-3}$) region. The absolute astrometry of the rest-

frame optical/UV, submm and radio positions (each $\pm 0.3''$) is not yet sufficient to establish with certainty the relative locations of the emission sources at different wavebands. Relative positions are more precise and indicate that the UV bright source is about $0.5''$ W or SW of the optical source, and both have a size of about $0.7''$, or 5.7 kpc. Likewise, we find that the different submm components are spread over $\sim 0.7''$, with the CO 7-6 and submm continuum about $0.3''$ to the SW, while the CO 3-2 emission is centered to the NE. Keeping in mind that these differences are marginally significant we note that the spatial offsets appear to be along p.a. 45° , the direction of the separation between the UV and optical line emission sources (Smail et al. 2003). The 1.3 mm continuum ($1.6 \times 10^{13} L_\odot$) is unresolved, with an upper limit of about $1''$. The gas mass estimated from the CO emission is about $5.4 \times 10^{10} M_\odot$, and the dynamical mass is $4.5 \times 10^{10} \sin^{-2} i M_\odot$ for an adopted source diameter of $0.7''$.

4. Discussion

Our observations of three SCUBA selected galaxies confirm the redshifts identified from rest-frame UV/optical spectroscopy, although for SMMJ09431+4700 the optical redshift is inferred from a source that is physically distinct from the submm source. Our data more than double the number of published, mm-confirmed SCUBA redshifts. In addition to the three galaxies discussed here, these are SMMJ14011+0252 ($z=2.56$; Frayer et al. 1999; Ivison et al. 2001; Downes & Solomon 2003) and SMMJ02399–0136 ($z=2.81$; Frayer et al. 1998; Ivison et al. 1998; Genzel et al. 2003). Our observations confirm that at least some SCUBA galaxies are luminous and gas-rich systems seen at a similar epoch to the UV-bright QSO and Ly-break galaxies populations (Boyle et al. 2000; Steidel et al. 1999).

All five SCUBA galaxies are rich in molecular gas. For the CO luminosity to gas mass conversion factor appropriate for local ULIRGs the median gas mass of the five SCUBA sources is $2.1 (\pm 1.7) \times 10^{10} M_\odot$, similar to the median molecular gas masses found in high- z QSOs (e.g. Alloin et al. 1997; Downes et al. 1999; Guilloteau et al. 1999; Barvainis et al. 2002; Cox et al. 2002) but about three times greater than those of local ULIRGs (Solomon et al. 1997). Assuming the most probable value for $\sin i=2/\pi$, the median ratio of gas mass to dynamical mass in the five galaxies is ~ 0.5 , again 3 times greater than in ULIRGs (Downes & Solomon 1998), and similar to the $z=2.72$ Ly-break galaxy cB58 (Baker et al. 2003). Four of the five systems are composite AGN/starburst galaxies in a complex environment, such as a merger/interacting system. The fact that the submm galaxies are complex systems is the more noteworthy as their redshift range is close to the peak of the merging assembly history of galaxy evolution. Perhaps the multiple nature of the SCUBA sources, along with the action of winds and outflows may explain how Chapman et al. (2003) were able to see strong UV line emission in sources as rich in gas and dust as the submm-population.

Relative to their gas reservoir, submm galaxies are very efficient emitters of radiation. The ratio of IR luminosity to gas mass in our five sources has a median of $380 \pm 170 L_{\odot}/M_{\odot}$, similar to high- z QSOs (750 ± 350), HzRGs (260 ± 70 ; Papadopoulos et al. 2000) and local ULIRGs (260 ± 160 ; Solomon et al. 1997), but significantly larger than local LIRGs and more moderate luminosity starbursts (45 ± 30 ; Solomon et al. 1997). A young starburst with a Salpeter IMF between 1 and $100 M_{\odot}$ has $\sim 10^3 L_{\odot}/M_{\odot}$. If most of the IR luminosity of our submm sources is due to star formation, their star formation efficiency must be high, or the IMF must be biased toward high mass stars.

Our observations strengthen the conclusion (e.g. Genzel et al. 2003) that the brightest submm galaxies ($S_{850} \sim 2\text{--}10$ mJy, corrected for lensing) have dynamical masses within the central few kpc that are comparable to massive, local early type galaxies ($M_{\text{gas}}+M_{\text{stars}} \sim m^* \sim 7 \times 10^{10} M_{\odot}$; Cole et al. 2001). Keeping in mind that our observations strictly give only upper limits or rough estimates of source sizes, we obtain a median dynamical mass of $5.5 \times 10^{10} M_{\odot} \sim 0.8 m^*$, for $\sin^{-2} i = \pi^2/4$. Current semianalytic models of star formation in hierarchical CDM cosmogonies have difficulties accounting for the observed space density of such massive baryonic systems at $z \sim 3$. These models predict too few m^* galaxies at that redshift, by about an order of magnitude, perhaps as a result of too slow baryonic cooling and low star formation efficiencies in the models (Genzel et al. 2003).

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Table 1. Observed Properties for the Three SMM Sources.

Source	Transition	Redshift	R.A. (J2000.0)	Decl. (J2000.0)	I_{CO} (Jy km s ⁻¹)	Flux (mJy)	Line Width (km s ⁻¹)
SMM J04431+0210 ...	CO(3–2)	2.5094 ± .0002	04 43 07.25	02 10 23.3	1.4 ± 0.2 ^(a,c)	...	350 ± 60
	CO(7–6)	...	...	...	≤ 0.8	...	...
	3.0 mm	...	...	...		≤ 0.3	
	1.3 mm	...	...	...		1.1 ± 0.3	
SMM J09431+4700 ...	CO(4–3)	3.3460 ± .0001	09 43 03.74	47 00 15.3	1.1 ± 0.1 ^(a,b)	...	420 ± 50
	CO(9–8)	...	...	...	≤ 1	...	...
	2.8 mm	...	...	...		≤ 0.4	
	1.3 mm	...	09 43 03.69	47 00 15.5		2.3 ± 0.4	
SMM J16368+4057 ...	CO(3–2)	2.3853 ± .0014	16 36 50.43	40 57 34.7	2.3 ± 0.2 ^(a,b)	...	840 ± 110
	CO(7–6)	~2.383	16 36 50.41	40 57 34.3	1.1 ± 0.2	...	...
	2.9 mm	...	...	...		≤ 1	
	1.3 mm	...	16 36 50.40	40 57 34.2		2.5 ± 0.4	

Note. — The astrometric accuracy is $\leq 0.3'' (= \sigma)$; Limits on I_{CO} and Flux are 2σ , and uncertainties include statistical errors, as well as absolute flux errors; Line Width is full width at half maximum (FWHM); Line Velocity and 1σ error rounded to 10 km s⁻¹; ^a No continuum subtracted; ^b Gaussian fit; ^c Frayer et al. (2003) report an upper limit of 2.5 Jy km s⁻¹ using the OVRO interferometer.

Table 2. Derived Properties for the Three SMM Sources.

Source	D_A (Gpc)	$A = \mu_L^e$	$D = 1''^a$ (Kpc)	L'_{CO}^a ($10^{10} \text{ K km s}^{-1} \text{ pc}^{-1}$)	$M_{\text{gas}}^{a,d}$ ($10^{10} M_{\odot}$)	$L_{\text{FIR}}^{a,f}$ ($10^{13} L_{\odot}$)
SMM J04431+0210 ...	1.66	4.4 ^b	1.8	1.0 ± 0.2	0.8	0.3
SMM J09431+4700 ...	1.53	1.2 ^c	6.2	2.7 ± 0.3	2.2	1.7
SMM J16368+4057 ...	1.68	...	8.1	6.9 ± 0.6	5.5	1.6

Note. — Adopting a flat cosmology of $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$; ^a Corrected for the lensing magnification μ_L , if applicable; ^b From Smail et al. 1999; ^c From Cowie et al. 2002; ^d Adopting a conversion factor $\alpha = M_{\text{gas}}/L'_{\text{CO}} = 0.8 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$. L'_{CO} is the apparent CO line luminosity corrected for the lensing magnification (Solomon et al. 1997); ^e Assuming equal flux amplification and linear magnification; ^f Obtained from $850\mu\text{m}$ flux densities (Blain et al. 2002).

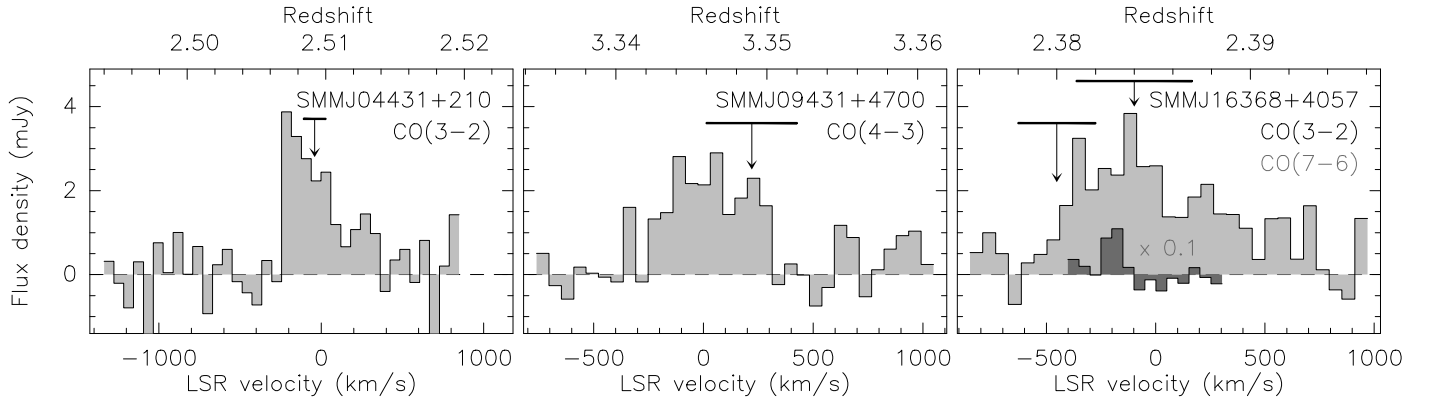


Fig. 1.— CO spectra of the three SCUBA sources. The LSR velocity scale is with respect to the CO redshift listed in Table 1. Optical redshifts (arrows, horizontal bars are uncertainties) are from Frayer et al. 2003 ($H\alpha + [N II]$, left panel), Ledlow et al. 2002 ($Ly\alpha$, center) and Smail et al. 2003 (UV photospheric + Seyfert 2), respectively. The rms noise per 20 MHz channel is 0.7, 0.9 and 0.6 mJy for the three sources, respectively (from left to right), in the spectral region where the frequency settings were overlapping, and increases to about 20 percent toward the edges of the bandpass. Overplotted on the CO 3-2 spectrum of SMMJ16368+4057 is the CO 7-6 spectrum scaled down to one-tenth of its flux density. The rms noise per 40 MHz channel is here 2.2 mJy.

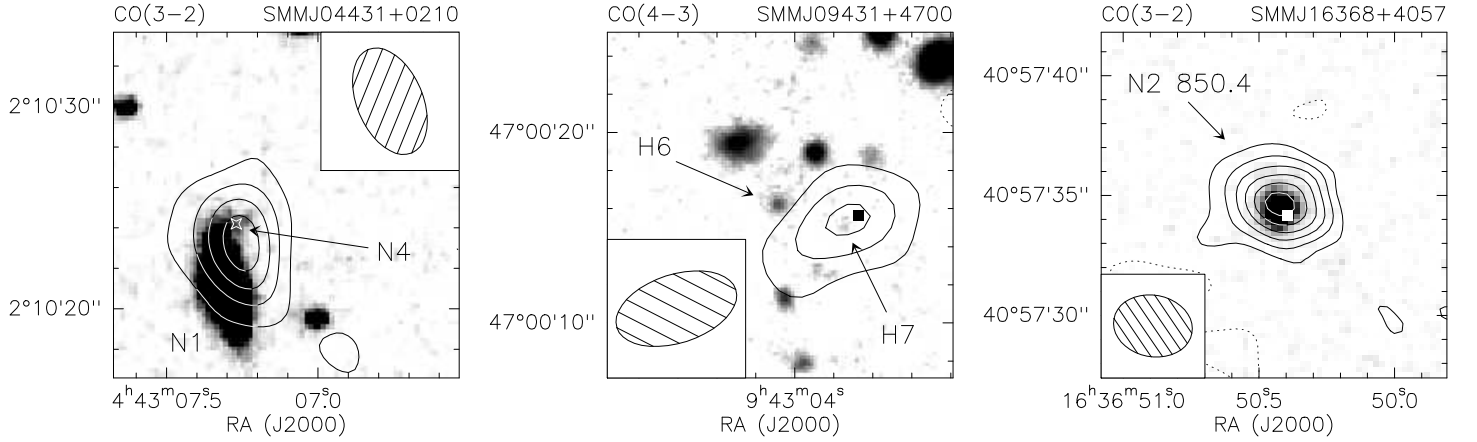


Fig. 2.— Velocity integrated, natural weighted CO maps of the three SCUBA sources, superposed on greyscale images of the optical emission. The contours are in units of 2σ of the noise level, and are 0.26, 0.31 and 0.20 Jy km s^{-1} in the three panels (left to right), respectively. The synthesized beams are (left to right, shown as hatched ellipses) $5.6 \times 3.3''$ at position angle 23° (E of N), $6.6 \times 3.6''$ at 108° , and $3.3 \times 2.6''$ at 79° . The three underlying images are in the *K*-band (left panel: Frayer et al. 2003, and right panel: Smail et al. (2003) and in the *I*-band (center panel: Ledlow et al. 2002). The asterisk (left image) is the position of the ERO N4 (uncertainty $\pm 0.5''$; see text), the filled squares (black and light) are the millimeter continuum positions (center and right). The edge on spiral galaxy $2''$ SE of the CO source is the source N1 in the foreground cluster at redshift $z=0.18$. In the middle panel the positions of the two radio sources H6 and H7 are denoted by arrows. The stronger optical and radio source H6 is a narrow line Sey1 galaxy at redshift $z=3.349$ ($\text{Ly}\alpha$). The CO 4-3 emission from N2 850.4 remains largely unresolved.